VORTEX-Southeast Program Overview

Erik Rasmussen
National Severe Storms Laboratory
Norman, Oklahoma

April 8, 2015

Contributors

This document was produced through a canvassing and blogging process involving an Interim VORTEX-SE Steering Committee. This committee was organized to identify scientific and logistical issues of VORTEX-SE in response a one-year allocation of funds in fiscal year 2015. Several anonymous individuals contributed to this process in addition to the following Steering Committee members:

Jonathan Blaes
Science and Operations Officer
National Weather Service
Raleigh, North Carolina

Mike Coniglio, Ph.D.
Research Scientist
National Severe Storms Laboratory
Norman, Oklahoma

Greg Forbes, Ph. D.
Severe Weather Expert
The Weather Channel
Atlanta, Georgia

Alan Gerard
Meteorologist-In-Charge
National Weather Service
Jackson, Mississippi

Kevin Knupp, Ph.D.
Professor
Atmospheric Science Department
University of Alabama in Huntsville
Huntsville, Alabama

Kevin Laws
Science and Operations Officer
National Weather Service
Birmingham, Alabama

Paul Markowski, Ph.D.
Professor
Department of Meteorology
The Pennsylvania State University
University Park, Pennsylvania

John R. Mecikalski, Ph.D.
Associate Professor
Atmospheric Science Department
University of Alabama in Huntsville
Huntsville, Alabama

Laura Myers, Ph.D.
Deputy Director
Center for Advanced Public Safety
The University of Alabama
Tuscaloosa, Alabama

Matthew Parker, Ph.D.
Associate Professor
Department of Marine, Earth, and Atmospheric Sciences
North Carolina State University
Raleigh, North Carolina

Erik Rasmussen, Ph.D.
Research Scientist; Program Manager, VORTEX-SE
Cooperative Institute for Mesoscale Meteorological Studies
University of Oklahoma
Norman, Oklahoma

Yvette Richardson, Ph.D.
Associate Professor
Department of Meteorology
The Pennsylvania State University
University Park, Pennsylvania

Contents

Contributors **2**

Introduction **5**

1 Scientific Goals and Hypotheses **7**
1.1 Meteorological Topics 8
1.1.1 Studies Utilizing Historical Data Sets 9
1.1.2 Mesoscale 14
1.1.3 Stormscale 20
1.2 Societal Impacts Topics 24

2 Experiment Overview **25**
2.1 Constraints 25
2.2 Climatological Considerations 26
2.3 General Deployment Template 27
2.4 Intensive Observation Periods and Forecasting 29

3 Instrumentation **30**

4 Data Sharing **30**

5 Detailed Planning **30**

6 Broader Impacts of VORTEX-SE **30**

Introduction

VORTEX-Southeast (hereafter VORTEX-SE) is a research program mandated by Congress to understand how environmental factors that are characteristic of the Southeastern U.S. affect the formation, intensity, structure and path characteristics of tornadoes for this region; to determine the best methods for communicating forecast uncertainty of these events to the public; and to evaluate public response.

Funding for VORTEX-SE consists of a one-year allocation to the National Severe Storms Laboratory. The Interim Steering Committee for VORTEX-SE was canvassed to provide thoughts on scientific, forecast, and public response issues that must be investigated to satisfy the Congressional mandate. Within the framework of a one-year effort, the plan described in this document has evolved, and will provide the greatest public benefit while simultaneously making any future tornado research programs in the Southeastern U.S. more effective.

In examining the distribution of tornadoes and tornado deaths in the U.S., Ashley (2007) found that the number of killer tornadoes in the Southeastern U.S. is disproportionately large when compared to the overall number of tornadoes (Fig. 1). Ashley (2007) attributed this finding to a "unique juxtaposition of a series of physical and sociological variables", including tornadoes at nighttime, in forested areas, prior to the perceived peak of the "tornado season", at a time of year when storms typically have large forward speeds. The study also identified lack of visibility, relatively inadequate shelter, and larger population density as being issues that increase the vulnerability of residents of the Southeastern U.S. VORTEX-SE will be the first severe storms experiment that will have a specific emphasis on addressing the sociologi-

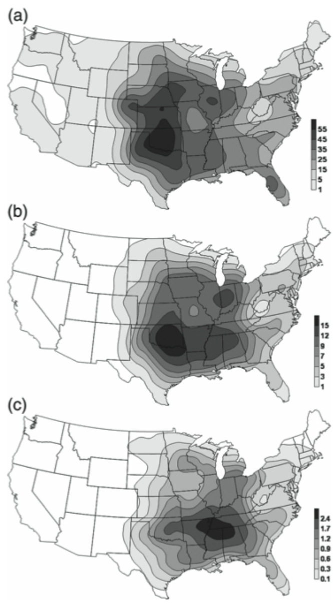

Figure 1: Fig. 6 from Ashley (2007). Smoothed frequency of the number of (a) tornadoes, (b) significant (F2+) tornadoes, and (c) killer tornado events in a 60 km x 60 km grid for 1950-2004.

cal factors that contribute to the relatively large tornado mortality in this region of the country.

Improvement in the quality of the warnings generated by the National Weather Service will be a focus of VORTEX-SE. One particular emphasis will be enhancements to the Forecasting a Continuum of Environmental Threats (FACETs) project. This is a proposed next-generation severe weather watch and warning framework that is modern, flexible, and designed to communicate clear and simple hazardous weather information to serve the public. FACETs supports NOAA's Weather-Ready Nation initiative to build community resilience in the face of increasing vulnerability to extreme weather and water events (see http://www.nssl.noaa.gov/projects/facets/ for details).

At the foundation of any effort to improve tornado warnings is the acquisition of new knowledge about the atmosphere, and the tools to utilize this knowledge. Several formal studies have recently appeared documenting meteorological issues that adversely affect tornado warnings in the Southeastern U.S. (Brotzge and Erickson, 2010; Brotzge et al., 2011; Brotzge and Donner, 2013; Brotzge et al., 2013). In broad terms, the issues include:

- It is now understood (Thompson et al., 2013) that there are regional differences in several tornado forecast parameters, including Convective Available Potential Energy (CAPE). Tornadoes in the Southeastern U.S. sometimes occur when CAPE is very small (0-500 J kg^{-1}; Sherburn and Parker, 2014). On the other hand, historical data also show that CAPE of the most unstable parcel is usually over 1000 J kg^{-1} somewhere in the neighborhood of the tornadic storm on a day in which tornadoes occur (cf. Sec. 2.2). In VORTEX-SE, we seek new knowledge of 1) whether/where local values of CAPE may be larger than those depicted by current analysis tools; 2) whether/when CAPE may grow larger for short periods of time, again unresolved in current analysis tools; and 3) whether, and for how long, storms can persist and possibly be tornadic in near-zero CAPE environments.

- Tornadoes in the Southeast occur during the night much more frequently than in other regions (Brotzge and Erickson, 2010), posing increased risk of tornado mortality (Sutter and Simmons, 2009; Ashley et al., 2008). New knowledge is needed concerning the ways nocturnal boundary layer evolution might be different from the common conceptual models, permitting storms to have near-ground processes supportive of tornado formation that normally are thought to be greatly hindered in stable nocturnal boundary layers.

- In complex terrain, beyond an idealized study by Markowski and Dotzek (2011), we have limited understanding of how the terrain and the larger-scale environment might be interacting to produce local pockets of conditions favorable for tornadic storms. Although the possible role of terrain in tornado development and changes in tornado intensity has been explored through idealized numerical experiments (Lewellen, 2012) and noted in some observational studies Forbes (1998), rudimentary analyses of historical data are yet to be conducted.

- Tornadoes from Quasi-Linear Convective Systems (QLCS; Weisman and Trapp, 2003) pose a major operational challenge. QLCS tornadoes often occur in environments with CAPE smaller than 500 J kg^{-1} (Thompson et al., 2013). These tornadoes sometimes appear to form through non-supercell processes, have shallower and more transient parent vortices (i.e. as detected on the scale, and at the lowest scanned elevations, of WSR-88D radar data; Davis and Parker, 2014), and sometimes are not detectable through dual-polarization debris signatures. Almost no concrete knowledge is available concerning their antecedent processes and signatures that might be detectable in radar data and provide improved lead time for warnings.

- In the Southeast, tornadoes sometimes occur when their parent storms appear to interact with features in the environment that produce short segments of reflectivity on radar (Knupp et al., 2013). The nature of these disturbances is unknown, making it very difficult to anticipate and understand which of these radar-detected features are likely to be associated with tornado formation, and which are not.

The new knowledge produced by VORTEX-SE should lead to significant improvements of analysis and forecast systems, and to improved forecaster understanding of the meteorology of southeastern tornadoes. This will improve lead times in tornado warnings, and allow anticipation of events that are presently missed because they do not fit the common conceptual models of tornadic storms.

1 Scientific Goals and Hypotheses

This chapter describes a set of scientific issues that are of current relevance to the southeastern U.S. tornado problem. It will not be feasible to address all of these issues within activities supported by the initial one-year funding, so this chapter represents a near-term (1-3 year) agenda for addressing currently known issues. To be most effective, these issues should be revisited on an approximately annual basis, allowing them to be refined in the light of new discoveries and new technical research capabilities.

1.1 Meteorological Topics

For each meteorological topic identified, we present a brief description, example testable hypotheses that can be used to focus discussion of data needs and operation plans, and needed observations. The observations are further classified as "essential" or "desirable". The topics fall into three broad classes: 1) Studies utilizing historical data sets; 2) Mesoscale, focusing on events at scales larger than individual storms, and including the effects of terrain on the storm environment; 3) Stormscale, focusing on internal processes of storms occurring in environments supportive of tornadoes. It is important to note that most of the topics in the Mesoscale and Stormscale categories are *suitable for both numerical and observational investigations*, and in fact could benefit from collaborative efforts between those approaches. Some of the Mesoscale and Stormscale topics also are suitable for investigating using historical data, and they are shown in the collection of historical topics (in slightly different form) as a way of emphasizing the importance of using existing data to lay the groundwork and strengthen the hypotheses for observational and numerical studies.

A few topics are marked "deferred". This means that resources, technology, timetables, or other factors will not allow the topic to be pursued in the spring of 2016, but that the committee believes the topic is important in the context of the Congressional mandate, and worthy of study if/when the research is supportable outside of VORTEX-SE.

In all matters related to funding opportunities, the specific funding announcements take precedence over this document; this Program Overview should be viewed as a supplement to give investigators a broader perspective of some of the issues of current concern in the scientific and operational community.

1.1.1 Studies Utilizing Historical Data Sets

Topographical Influences on Tornadoes	
Description	Preliminary idealized modeling (Lewellen, 2012) and a few historical studies (e.g. Forbes, 1998) show that terrain likely plays a role in tornado motion and intensity. Although these studies suggest that the problem is complex and that there is no typical pattern of effects that fits all tornadoes, it is important to establish if there are common roles for topographical influences in tornado formation and intensity. This would provide motivation, justification, and direction to further observational and numerical studies of these influences. Topographical influences can best be examined using historical data of tornado formation location, as well as intensity along the damage path for events with accurate damage assessments. (Note that another topography-related topic can be found in Sec. 1.1.2)
Example testable hypotheses	Tornado formation location is favored by certain levels of terrain variability. Tornado formation is favored by particular values of terrain slope. Tornado damage intensity is correlated with terrain slope.
Needed observations (essential)	Historical tornado data, including variations in intensity along the tracks. Topographic data.

Analysis of Wave-like Reflectivity Segments	
Description	We have noted for almost a decade that wave-like reflectivity features that we term "wave-like reflectivity segments" [WRS; Knupp et al. (2013)] are common in the severe storms environment, particularly during the cool season when high shear, low CAPE environments are common. These appear as small features moving with a very deviant motion vector compared to mature storms. The correlation between WRS and storm intensification and/or tornado production has not been formally established. Hence, this topic appears in the historical data analysis section because it seems to be amenable to an analysis of existing WSR-88D data. In particular, objective means of identifying WRS, determining the time of WRS/storm interaction, and measuring response in reflectivity and/or velocity data, should be used. Further, to the extent feasible, this topic should include examination of storm/storm interactions during mergers. (Note that the topic "Characterization of Wave-like Reflectivity Segments" can be found in Sec. 1.1.2)
Example testable hypotheses	Low-level rotational velocity trends are correlated with stages of WRS/storm interaction.
Needed observations (essential)	Historical WSR-88D data

Surface Roughness Influences on Tornadoes	
Description	Surface roughness, as measured by roughness length, is known to affect the corner region flow of a vortex. Hence it is plausible that tornado formation location, and changes in tornado intensity, are correlated with roughness. A useful proxy for roughness might be Land Use/Land Cover data. This is a topic in the historical data analysis section because it would be useful to determine if any correlation exists between roughness and tornado behavior before conducting much more difficult (perhaps infeasible) field observations of the role of terrain roughness in individual tornado events. (Note that another roughness-related topic can be found in Sec. 1.1.2)
Example testable hypotheses	Tornado formation location is correlated with surface roughness. Changes in tornado intensity are correlated with surface roughness.
Needed observations (essential)	Historical tornado data, including variations in intensity along the tracks. Land Use/Land Cover data.

QLCS Damage and Radar Signatures	
Description	Davis and Parker (2014) generated a comprehensive historical analysis of WSR-88D signatures related to tornadoes in the Southeast U.S., including QLCS tornadoes. This work can now be augmented by greatly improving the damage characterization for these events, continuing to research the utility of dual-polarization Tornado Debris Signature [TDS; Van Den Broeke and Jauernic (2014), Bodine et al. (2012)] for vortex confirmation, and further exploring other radar signatures that may be antecedents for QLCS tornado formation such as ZDR arc, and horizontal separation of KDP and ZDR (Crowe et al., 2012). It is of special interest to determine the nature of the damage in terms of rotational, convergent, and straight velocity components implied by damage patterns. Some of this work can rely on existing data if comprehensive high-quality (e.g. the entire path documented photographically from aloft) surveys are available.
Example testable hypotheses	QLCS tornadoes within 30 km of a radar site, not exhibiting a TDS, have damage dominated by straight flow components. QLCS tornadoes are preceded by a single-Doppler wind signature dominated by convergence.
Needed observations (essential)	Historical and future routine WSR-88D data. Historical and future aerial photographic track documentation.

Mid-tropospheric Phenomena	
Description	It has been noted for at least two decades that Cold Fronts Aloft (or "Split Fronts") can produce episodes of highly organized severe convection in the Southeast U.S., even including in the presence of Cold Air Damming from Virginia to northern Alabama. Published cases include 14 February and 10 January 2000 (Brennan et al., 2003), 18-19 December 1995 (Koch, 2001), and 21-23 January 1999 Koch and Mitchem (2003). The degree of correlation between CFA events and tornado production in the Southeast U.S. has not been formally established. Fortunately, there exists a systematic process for identifying the presence of CFA phenomena that only requires use of historical WSR-88D, mesoscale model data (e.g., HRRR, RUC), and enhanced satellite imagery (Koch, 2001). In particular, CFA features can be readily detected in mesoscale model fields of mid-level equivalent potential temperature, kinematic frontogenesis, and ageostrophic winds, and analyses of isodops and retrieved thermal advection (assuming geostrophic shear) from the WSR-88D Velocity-Azimuth Display fields.
Example testable hypotheses	An analysis of existing data will reveal that Cold Fronts Aloft are a prolific producer of organized systems of severe thunderstorms and tornadoes in the warm sector hundreds of kilometers ahead of any surface cold front, and can be readily detected using the systematic method outlined in (Koch, 2001). Previous studies that have indicated that CFAs produce both convective instability and the mesoscale mechanism to release that instability (through ageostrophic mid-tropospheric frontal circulation) will be validated with this large dataset. It will be shown that the necessary and sufficient conditions to produce these storms consist of strong diagnosed frontal vertical motions of sufficient duration operating upon a moderately unstable and moist lower troposphere to be able to raise surface-based parcels to their Level of Free Convection.
Needed observations (essential)	Historical WSR-88D data using the NSSL MYORSS reanalysis datasets being produced jointly with NCDC. Archived mesoscale model fields from UCAR.

1.1.2 Mesoscale

Inter-band Differential Heating in Tropical Cyclones (deferred)	
Description	Clearing between convective bands may be leading to a substantial increase in CAPE, and an alteration in the local shear profile through thermally direct circulations, by heating the near-ground air in an otherwise nearly moist adiabatic environment (Baker et al., 2009). Details of the thermodynamic profiles are partially influenced by dry air intrusions in some tropical cyclones.
Example testable hypotheses	The cross-band distribution of CAPE and low-level shear is consistent with the effects of local heating due to insolation between tropical cyclone convective bands.
Needed observations	Mobile mesonet observations of local surface parcel state (desirable). Boundary layer profiler to evaluate local changes in boundary layer stability (essential). Doppler Lidar and/or SODAR to evaluate circulations that develop in response to local/banded heating (essential). Soundings (essential). Pyranometer (essential). Satellite cloud observations (essential).

Characterization of Wave-like Reflectivity Segments	
Description	As described in the topic in the historical data analysis section, WRS (Knupp et al., 2013) appear to be common in the severe storms environment, particularly during the cool season when high shear, low CAPE environments are common. We have acquired some recent comprehensive data sets that include soundings, profiling observations, and dual Doppler analysis of both the WRS feature and storm individually, as well as their interaction. We find repeatedly that upon intersection of a fast-moving WRS (or a series of WRSs) with a convective core within a QLCS, or supercell storm, that an increase in low-level rotation is observed. What are these features? Because the nature of the features is essentially unknown, the following strawman hypothesis is given in order to produce the initial observational data needed to characterize the WRS.
Example testable hypotheses	WRS have perturbations in 3D velocity, surface pressure, and thermodynamic profiles, consistent with gravity waves.
Needed observations	Boundary layer profiler (desirable). Doppler Lidar/SODAR boundary layer velocity measurements (desirable). Soundings (desirable to characterize supported wave types). Dual- or multi-Doppler velocity observations to characterize motion perturbations (essential). Satellite cloud observations (desirable).

Terrain Influences on the Severe Storm Environment	
Description	In this topic, we include topographic effects that are suitable for studying with observational data sets (cf. the Topographical Influences on Tornadoes topic). This description is motivated by the work of Markowski and Dotzek (2011). That study concluded that the dominant positive (negative) influence of terrain on supercells is through creating local environments that would normally be regarded as conducive (detrimental) to the storms. An additional terrain effect could be the formation of local mesolows akin to the Denver Convergence and Vorticity Zone (Szoke et al., 1984). Note that this topic does not include direct observation of tornado/terrain interaction, which is considered to be infeasible at this time. Addressing this topic will likely require analyses based on a data assimilation approach that utilizes the observations to form a valid coherent analysis of the terrain effects. Development of this technology would benefit from sample data sets for prototyping.
Example testable hypotheses	Upslope flow with respect to mesoscale topographic features is associated with increasing CAPE, and decreasing CIN; downslope flow with the opposite effect. Variation in boundary layer airflow (hence potential for tornado formation and/or intensity change) can be generated in regions of topographic variation by: a) channeling, b) enhancement of airflow over a ridge. Low level shear is enhanced over ridges/plateaus.
Needed observations	Doppler radar volumes with minimized terrain-related obscuration (essential). Boundary layer wind profilers (essential). Mobile mesonet (essential). Soundings at upslope and downslope locations with respect to mean BL flow (essential). Satellite cloud observations (desirable).

Nocturnal Boundary Layer and Storm Maintenance	
Description	Forecaster experiences indicate that the nighttime environment and its role in potentially tornadic convection is very poorly understood. In particular, concerns have been raised regarding whether CAPE is under-analyzed and under-forecast because of a poor model representation of the boundary layer and its vertical structure. It is also possible that favorable combinations of CAPE and low-level shear exist in local pockets that are unsampled or unrepresented in current analysis and NWP products.
Example testable hypotheses	Vertical stratification and its effect on CAPE are misrepresented in operational and real-time demonstration NWP models. CAPE sufficient for maintenance of potentially tornadic storms exists in horizontal patches that are unresolved in operational prediction models.
Needed observations (essential)	Lidar/SODAR wind profiling. Soundings. Boundary layer thermodynamic profiling. Multiple-Doppler wind analyses.

Maintenance of Large Boundary-Layer Vertical Shear	
Description	Vertical shear in the low levels, thought to be essential for supercell tornadoes, is often unexpectedly large through the daytime hours. This could be related to suppressed vertical mixing of momentum when the boundary layer remains (at least slightly) stable. This maintenance might be the result of reduced insolation in the presence of persistent cloudiness.
Example testable hypotheses	On average, mesoscale forecast models depict a more well-mixed daytime boundary layer than is observed in the presence of cloudiness.
Needed observations (essential)	Lidar/SODAR wind profiling. Soundings. Boundary layer thermodynamic profiling. Satellite cloud observations.

Rapid Destabilization	
Description	In general, tornado events in the Southeast U.S. are extremely strongly forced (strong cold fronts, strong low-level jets, strong upper tropospheric support for QG ascent). One way to assess the effects of the strong forcing is to evaluate the rate of convective destabilization, itself important in forecasting the onset and severity of convection. For situational awareness, it is important to recognize the processes leading to the destabilization.
Example testable hypotheses	Processes leading to rapid increases in CAPE are dominated by low-level temperature and moisture advection.
Needed observations (essential)	Serial soundings. Passive radiometric profiling.

Boundaries and Roll-like features	
Description	The influence of boundaries received quite a bit of attention, starting with VORTEX-94 and VORTEX-95 observations, but has not been pursued systematically since these earlier studies. Additionally, forecaster experience has shown that both pre-frontal confluence lines and roll-like features in the boundary layer - possibly horizontal convective rolls (HCRs)- may play an important role in storm initiation in warm-sector environments away from synoptic-scale boundaries. New knowledge is sought concerning roll-like features and boundaries in the Southeastern U.S. including diffuse boundaries, their relationship to surface fluxes and land use, and the role of terrain in producing boundaries (e.g. through cold air damming) or affecting their evolution. From the perspective of improving understanding of benefit to operational meteorology, quasi-linear boundary- or roll-like features can be apparent in satellite, radar, and surface data. It would be beneficial to know what these features are in terms of their wave properties, baroclinity, and circulations on multiple scales. This would provide insight into their potential for CI and modification of existing convection. This topic envisions a deployment in which a boundary or pattern of roll-like features is comprehensively sampled when it is identified in conventional data. In general, the nature of boundary layer inhomogeneities that are important in tornadic storm environments are poorly understood.
Example testable hypotheses	In southeast U.S. severe-storm environments, HCRs with attendant streamers of vertical velocity occur frequently in the warm-sector boundary layer in environments that support severe convection and are an important mechanism for the initiation and maintenance of convection away from larger-scale boundaries. The supportive effects of these HCRs on convective initiation are not depicted well in NWP model simulations that use 2-4 km grid spacing, but are depicted well with grid spacing smaller than 1 km. Initial observations should lead to other readily testable new hypothesis.
Needed observations (essential)	Dual- or multi-Doppler velocity measurements (essential). Soundings on either side of boundaries (essential). Sticknet (desirable). Mobile mesonet transects (essential). UAV transects (essential). Boundary-layer profilers deployable for several-hour periods (essential). Satellite cloud observations (desirable).

1.1.3 Stormscale

Downdraft Forcing	
Description	Thermodynamic characteristics of rear frank downdrafts (RFDs), which can affect tornadogenesis, are determined in part by microphysical processes such as evaporation of raindrops and melting of hailstones (Markowski et al., 2002). There will be opportunities to use dual polarization radar (e.g., Carey et al. 2010; Kumjian et al. 2011) and ground based measurements (e.g., disdrometers) to characterize microphysical properties (e.g., hydrometeor types, shape, size, concentration) and processes (e.g., melting, evaporation) in and around the RFD of tornadic and non-tornadic supercells, as well as in QLCS where convective-scale downdraft tilting is known to contribute to the development of vertical rotation (Trapp and Weisman, 2003; Wheatley and Trapp, 2008), and other supercell downdrafts.
Example testable hypotheses	Low-level downdraft maxima are always associated with local maxima in hail concentration in the column above, inferred using dual-polarization radar data, and/or local maxima in concentration of large drops at the ground inferred through disdrometer measurements.
Needed observations	Rapidly deployable disdrometer, guided by realtime radar information (desirable). Dual-polarization radar data (essential). Dual- or multi-Doppler radar data for vertical velocity (essential). Mobile mesonets for downdraft parcel buoyancy observations at the ground (desirable). Satellite cloud observations (desirable).

Horizontal Vorticity Streamer	
Description	Unpublished research (Rasmussen, personal communication) shows that in some supercells, the vorticity that eventually comprises the tornado cyclone moves along the ground in a concentrated region about 250 m deep and perhaps 1000 m across. This feature is comprised largely of horizontal vorticity, and has been dubbed "Horizontal Vorticity Streamer" (HVS). Possible similar features can be seen in supercell simulations by Wicker and Wilhelmson (1995); Gaudet and Cotton (2006); Beck and Weiss (2012). When this feature, emanating from the supercell precipitation core, encounters an updraft that extends close enough to the ground with enough intensity, the horizontal vorticity streamer turns abruptly upward into the low-level updraft with subsequent stretching producing a tornado cyclone. The shallow depth of the horizontal vorticity streamer implies that it will not be observed in dual-Doppler data; not even in mobile deployments without extreme luck. This motivates the following hypothesis:
Example testable hypotheses	There exist streamers of horizontal vorticity adjacent to the ground between the precipitation core and the low-level updraft with horizontal vorticity in excess of 0.2 s^{-1} through a depth of 250 m. The streamers of near-ground vorticity have the vertical component of vorticity exceeding the horizontal component.
Needed observations	UAV in a formation capable of measuring wind at four points (e.g. the "flying vorticity meter formation.")

QLCS Tornadogenesis	
Description	The formation mechanics of QLCS tornadoes, common over the Southeast (e.g. Davis and Parker, 2014) and northern Alabama in particular, are largely unknown. While QLCS tornado events are common over the SE, and N AL in particular . Three candidate mechanisms can be found in the literature based on studies of events in other parts of the U.S: updraft tilting of horizontal vorticity (Atkins and St. Laurent, 2009), downdraft-tilting of internally generated horizontal vorticity (e.g. Lee and Wilhelmson, 1997; Trapp and Weisman, 2003; Wheatley and Trapp, 2008), and vortex intensification within a vortex sheet that is created by slab tilting of boundary layer air at the QLCS gust front [reminiscent of shearing instability (Wheatley and Trapp, 2008) but perhaps a different mechanism]. All of the above mechanisms require low-level stretching for vortex intensification. This is a topic that probably requires an initial set of high-quality observations and process studies before high-quality testable hypotheses can emerge. Below we propose strawman hypotheses, and of which would be suitable to drive the collection of the needed data.
Example testable hypotheses	QLCS tornadoes are produced by shearing instability along the leading edge gust front. QLCS tornadoes occur due to updraft tilting of storm-generated horizontal vorticity. QLCS tornadoes occur due to downdraft tilting of storm-generated horizontal vorticity.
Needed observations	Dual- or multi-Doppler wind data (essential). Mobile mesonet observations of storm-scale near-ground buoyancy fields (desirable). UAV thermodynamic observations (desirable). Post-storm damage surveys to verify tornado events (essential).

Internal Processes, Lightning, and Cloud-top Features	
Description	In recent years, considerable effort has been made to develop severe weather nowcasting tools using rapid-scan satellite imagery (in anticipation of GOES-R) and total lightning mapping (e.g. Bedka et al., 2015, and references therein). Most of these tools are based on the assumption that what is measured in satellite and lightning data can be used to infer updraft strength, and updraft strength can be used as a proxy for severe weather likelihood. This VORTEX-SE topic is intended to develop new knowledge about the internal processes of potentially tornadic storms and their relationship to lightning (e.g. total, flash size, cloud-to-ground ratio) and satellite observables (e.g. overshoot tops, brightness temperature, enhanced U/enhanced V signatures, above-anvil cirrus plumes). This topic does not include algorithm design or testing.
Example testable hypotheses	Changes in the updraft and downdraft structure and strength of observed storms are associated with consistent signatures in satellite and total lightning data. Early convective initiation signatures in cumulus cloud growth and microphysical characteristics are uniquely distinct for storms that later go on to produce severe weather (as compared to those that do not).
Needed observations	Dual- or multi-Doppler wind data (essential). Rapid-scan satellite imagery (essential). Total lightning mapping (essential).

VORTEX-SE will include two efforts in Numerical Weather Prediction (NWP) at NOAA Laboratories. At the National Severe Storms Laboratory, Warn-on-Forecast experiments will be conducted. These will consist of two periods of two weeks each where the current NSSL system will be tested to see if it can provide useful one-hour guidance in the VORTEX-SE area.

The Earth System Research Laboratory (ESRL), will conduct research with an experimental version of the High Resolution Rapid Refresh (HRRR) model to form high-resolution background error covariance information from a storm-scale ensemble-hybrid data assimilation system. Further, ESRL will be testing the new 4DDA system for a tornado event within the Hazardous Weather Testbed. One focus of this research will be on the variety of different tornadic-storm producing environments in the Southeastern U.S.

Researchers interested in participating in VORTEX-SE are encouraged to think about ways to increase the synergy between observational work and these two NWP efforts, as well as other efforts that are proposed.

1.2 Societal Impacts Topics

In addition to the meteorological research, recognizing the important goal of making improved forecasts and warnings available to the public in the most effective manner, VORTEX-SE will be supporting research into some of the topics listed here.

Lead time

The objective of this research is to evaluate how the public and the weather enterprise in the southeast interpret lead-time. The NWS defines lead-time from the issuance of the warning, but it's actually when the public and the weather enterprise receive the warning that actually initiates the lead-time.

False alarms

One of the unique aspects in the southeastern United States is the preponderance of more frequent, short-lived, low-end events, which often lead to high false alarm rates (FAR). The high FAR is associated with low lead-time and missed events. The objective of this research is to evaluate public perceptions of "false alarms" There is significant concern in the southeast about too many false alarms and how this may desensitize the public. There have been many changes in the tornado warning process with greater use of the warning polygon and more precise warning geography.

Nocturnal events

The objective of this research will be to evaluate how the public understands nocturnal events and how they obtain and use nocturnal weather warnings. It is important to first understand if the public generally understands that nocturnal tornadoes can occur. Once they understand that nocturnal tornado events occur, how do they plan to obtain warnings at night?

Shelters

The objective of this research will be to evaluate shelter knowledge and shelter usage by the public. This investigation will include changes in perceptions regarding the need for stronger shelters in high-end events, changing patterns of shelter use, etc.

Sirens

The objective of this research will be the evaluation of the use of sirens for tornado warnings. Even with warning polygons, many counties in the SE still warn the entire county with sirens. This research will explore the reliance on sirens at the county level, the public response to sirens, and how siren use contributes to the perception of false alarms.

Television communications

The objective of this research will be to evaluate how TV meteorologists have modified their risk and crisis communication for potentially high fatality events.

Changes in communication and planning for high fatality events.

The objective of this research is to evaluate how all emergency planners in the weather enterprise handle communication and planning for potentially high fatality events. This will include studying how the communication and planning process has been modified after previous high-fatality events, and whether overreaction to previous high-fatality events has led to desensitization and fatigue.

Complacency

The objective of this research will be to evaluate the potential complacency in risk communication, preparedness, and weather awareness that can develop with extended time periods between severe weather events.

2 Experiment Overview

2.1 Constraints

The first field experiment of VORTEX-SE has been designed to most effectively address the specific, testable hypotheses described in Section 3. The following constraints were important in the design process.

- Terrain and Land Use. While a first inclination might be to repeat the wide-roaming, fully-mobile approach of VORTEX and VORTEX2, these concepts would be impossible to implement in the southeastern U.S. because of terrain and land use. At a fundamental level, it is simply not safe to sample severe storms in a fully mobile fashion when the storms are not clearly visible because of terrain, trees, low clouds, and low visibility. Further, the previous VORTEX experiments took advantage of areas with grids of roads (often on one-mile section lines) to facilitate rapid mobility; this sort of mobility is not available in much of the southeastern U.S. Even with easy mobility, it proved challenging in VORTEX and VORTEX2 to deploy observing systems in a scientifically optimal manner.

- Climatology. Considering a single location in the Southeastern U.S. (Huntsville, AL), there is a clear "storm season" during which research is most likely to be fruitful. This is discussed more below in Sec. 2.2.

- Available Instrumentation. Because of certain aspects of the timetables and available funding processes of VORTEX-SE, special consideration must be given to available instrumentation. This is described below in Sec. 3

2.2 Climatological Considerations

The following is some pertinent climatological information for the Huntsville, AL area. This area is a subtle geographical maximum in tornado probability for the Southeastern U.S. in late March; a second maximum is found in central Mississippi in November.

The area within 120 km of the ARMOR radar site has experienced 300 tornadogenesis events in 10 years. The median number of tornadoes per year within that circle is 26 with a minimum of 11 and a maximum of 61. Note that these are not all March/April tornadoes, although that is the peak season (Kevin Knupp; personal communication).

Storm Prediction Center climatological data (courtesy of Andy Dean) shows that within 100 km of Huntsville, in 13 years of data for March and April, there are a median of 12 episodes of lightning, where an episode is defined as one or more contiguous "convection days" (12 UTC - 12 UTC) of activity. An Intensive Observing Period (IOP) likely would span an episode plus a day of observing atmospheric evolution before convection commenced.

These data also show that tornado episodes in March and April tend to be of one day duration, or, much less frequently, two days. These are embedded in episodes of convection that are slightly longer. There have been 26 episodes of March/April tornadoes within the 100 km circle in the last 13 years, with a median of 2, a minimum of 1, and a maximum of 5. In contrast, in the month of February, 11 out of 13 years have had zero tornado episodes, with two years having one or two episodes. So the prospects of successful observational deployments in March and April are much higher than February.

It can be seen that the combination of shear and CAPE on tornado days (Fig. 2) in the climatology is in the upper range of that observed on days with no tornadoes (but having lightning). For example, for maximum SPC mesoanalysis 0-1 km shear > 40 kt and CAPE > 1000 J kg^{-1}, there are 19 tornado days and 30 non-tornadic thunderstorm days. So given a perfect model being used for forecasting, observing the entire 100 km radius range centered on Huntsville, and deciding to deploy when those two criteria are met, we would expect to observe at least one tornado on about 40% of the IOPs. And tornado days frequently have more than one tornado.

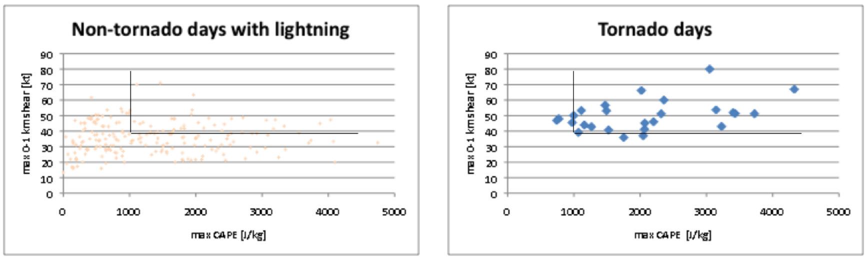

Figure 2: For the period 2003-2013, in the months of March and April, convection day maxima of most-unstable CAPE (J kg^{-1}) vs. 0-1 km shear vector magnitude (kt) for all days with lightning but no tornadoes (left); and days with tornadoes (right). Area is within a 100 km radius of Huntsville, AL. Data courtesy Storm Prediction Center.

2.3 General Deployment Template

These concepts represent the likely observing scenarios in VORTEX-SE. They are provided in this document to aid researchers in developing proposals and to guide later detailed planning.

Almost all of the science objectives of VORTEX-SE fit cleanly into the concept of deployments tethered to available WSR-88D sites (often with nearby TDWR sites). This concept was first put forth for VORTEX2, but was not utilized because of a lack of storms near the chosen “tether post” in central Oklahoma. In VORTEX-SE, the observing domain will be roughly within 100 km of a fixed location. To the extent possible, we will leverage locations with concentrations of existing instruments, such as the area around the University of Alabama at Huntsville (Fig. 3). It is possible that during detailed planning, especially considering the short duration of the first-year observing window, the Huntsville area will be selected as the only viable location for observations. However, prior to detailed planning, the following sites with WSR-88D radars will also be assessed for viability by the VORTEX-SE Program Manager: Memphis TN, Columbus, MS, Slidell LA, Mobile AL, Jackson MS, Nashville TN, and Fort Campbell KY.

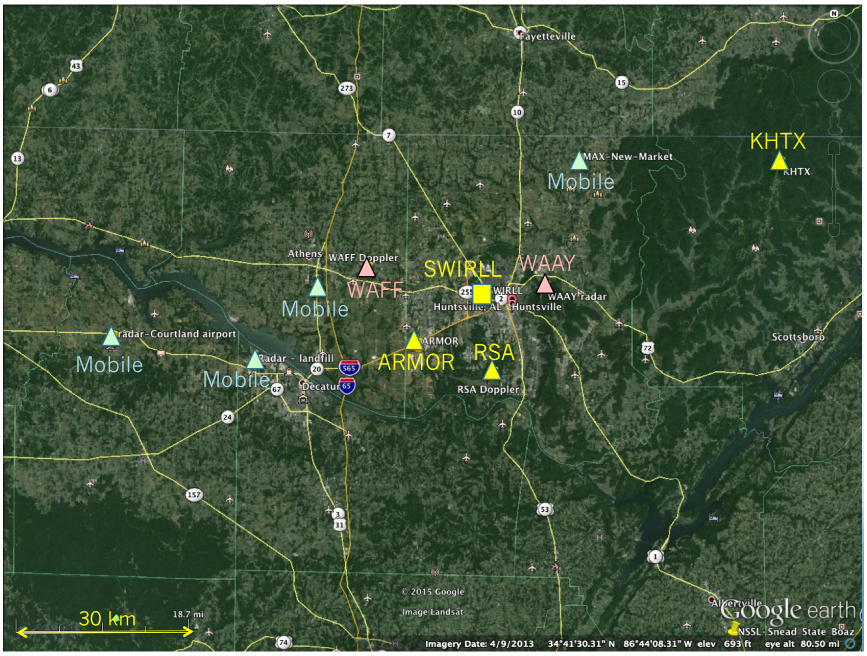

Figure 3: Example of some of the existing and potential observing infrastructure near the University of Alabama at Huntsville (image courtesy of Kevin Knupp). Yellow triangles are existing radar locations, while pink triangles denote the location of radars that could be upgraded for data collection. Blue triangles denote sites suitable for operation of mobile radars.

For each deployment location, based upon the mix of observing systems that are available (not known until after the funding process is completed), pre-planned fixed observing sites will be selected for each platform based on terrain, land use, and the meteorological objectives (tools for doing this evaluation have been developed by Conrad Ziegler for the PECAN field experiment).

Certain platforms may have limited mobility if the selected research activities require it. For example, mobile mesonets, mobile soundings, UAV systems, etc. might require some mobility. For each deployment location, GIS data will be used to choose likely optimal roads and highways to facilitate mobile sampling.

Depending on the eventual mix of research activities, it is likely that deployments will have durations of 2-4 days. There are several research topics that may require continuous data collection during the observing period.

2.4 Intensive Observation Periods and Forecasting

For some researchers, it would not be financially or logistically possible to be present in the field for the entire period of March and April. Because of the episodic nature of severe storms in the southeast, related to the passage of synoptic scale disturbances, it should be feasible to obtain many observations in the context of Intensive Observation Periods (IOP; this does not exclude some topics that benefit from continuous season-long observations). Hence, IOPs will be conducted when classical CAPE and shear combinations are forecast to be supportive of tornadoes (see Sec. 2.2). It is likely that some research topics will require the IOP to include a 24-hour lead-up to the severe weather event.

Limited subjective monitoring of forecast products in 2015 indicates that it should be possible to put VORTEX-SE on an "IOP Watch" about 10 days before an IOP is executed, based on signals in the GFS and CFS. Additional evaluations of this approach are ongoing. During an IOP watch, discussions amongst all investigators would be ongoing regarding the forecast, and individual investigators would begin to make contingency plans for possible deployment.

During the IOP Watch, and no later than about five days before the forecasted lead-up day, a go/no-go decision would be made. The chance of a complete bust is small because of the fairly well-forecast synoptic patterns likely to be targeted in VORTEX-SE. The odds are much greater that a 1-2 day error would be made in selecting the start date, and/or that the event is not as extreme as expected. The latter is not very concerning because many of the VORTEX-SE science topics will benefit from well-collected data even if tornadic storms are lacking. At the "go" decision, investigators would implement their travel plans and move to the chosen deployment location.

In some cases, the overall pattern becomes active with lower-amplitude waves in strong zonal flow. This could lead to the potential for a succession of IOPs with only short breaks between. So it will be important to plan travel accordingly, with the best strategy likely being to stay on site between the IOPs.

Note that this concept does not preclude investigators being stationed in Huntsville or some other location central to the potential deployment sites for the entire two month period.

Based on historical data, it is likely that 2-6 IOPs would be conducted in March and April 2016, with a slight chance that investigators will decide to conduct an IOP as early as February. Later planning and budget analysis might lead to that number of IOPs being capped.

The framework for forecasting for VORTEX-SE operations has not been determined, but will be established in subsequent planning activities.

3 Instrumentation

(+++ rewrite for consistency with FFO; referring to web page) Because of the limited funding and timetable of VORTEX-SE, it will not be possible to broadly support the development or acquisition of instruments. Hence researchers will have to rely on existing equipment that they own or have access to, or to the extent possible utilize collaborations with others who have access to instruments. Once the funding process is concluded (no later than the end of the fiscal year) it will be possible to assess the availability of various instruments and refine the deployment plans.

In addition to the instruments shown in Fig. 3, it is likely that two MIPS (`http://vortex.nsstc.uah.edu/mips/system/`), one MAX radar (`http://vortex.nsstc.uah.edu/mips/max/`), and one CLAMPS (`http://www.nssl.noaa.gov/users/dturner/public_html/CLAMPS/slide01.html`) will be present for VORTEX-SE, and that the NOAA Air Resources Laboratory (ARL) will operate a 30 m instrumented tower and a profiling UAV (octocopter) at a site near Huntsville.

4 Data Sharing

Per NOAA requirements, environmental data and information, collected and/or created under NOAA grants/cooperative agreements must be made visible, accessible, and independently understandable to general users, free of charge or at minimal cost, in a timely manner (typically no later than two (2) years after the data are collected or created), except where limited by law, regulation, policy or by security requirements.

Further, it is expected that VORTEX-SE investigators will take all necessary actions to make sure data are promptly archived in safe, redundant storage, and will properly attribute data sources in all publications and other uses.

5 Detailed Planning

During the fall and winter of 2015-2016, additional activities will be organized by the VORTEX-SE Program Manager focused on developing an Operations Plan for the spring 2016 field phase. The purpose of an Operations Plan is to provide all participants with the detailed information they need to adequately prepare for, and conduct, their specific missions.

Preceding the operations planning, in the summer of 2015 a scientific workshop will be conducted in the southeastern U.S. This workshop will *not* serve to guide planning activities for the initial one-year funded activities of VORTEX-SE, and the 2016 field phase. Instead, the purpose of this workshop will be to develop an agenda for further research that can be used to inform the planning activities of all government agencies. It will attempt to develop a consensus of issues in atmospheric science, social science, and operations as they pertain to the Southeast U.S.

6 Broader Impacts of VORTEX-SE

Beyond the specific meteorological and social science objectives detailed above (Sec. 1), VORTEX-SE is likely to have the following broader impacts.

Establish longer-term research needs and build the foundation. Given the constraints of the initial VORTEX-SE activity, the planning process has been conducted with the goal of providing new insights that can clarify, and motivate, future research. The initial work should allow the research community to greatly improve the working hypotheses, and allow it to target future observations in an increasingly efficient manner.

Begin to apply state-of-the-art computer models to forecast tornadoes in rugged terrain. VORTEX-SE will involve research and development of forecast models that are capable of representing convection in complex terrain, including the NSSL Warn-on-Forecast approach.

Improve warnings and public response to warnings. One emphasis of VORTEX-SE is on many of the factors shaping public response to tornado warnings. The activities that will contribute to improvement in tornado warnings are described in the Introduction and the Science Objectives.

Improve damage assessment. One of the scientific objectives requires detailed aerial mapping of tornado damage swaths. If supported, this should be the first test of technology to routinely provide these assessments. Quality assessments of tornado events are very important for understanding the phenomena that produce the damage, and for improvements in Probability of Detection and False Alarm Ratios.

Establish utility of gap-filling radar systems. Because VORTEX-SE will utilize radars in addition to the network WSR-88D and TDWR radars, it will be straightforward to determine if detections of tornadoes (or likewise rejection of non-tornadic events) can be improved with gap-filling radars. Similarly, the improvement in model forecasts through assimilation of gap-filling radar data will be assessed in VORTEX-SE.

Establish the utility of routine boundary layer profiling. VORTEX-SE will utilize instruments that are capable of measuring the thermodynamic variables and wind in the boundary layer with high temporal resolution (e.g. every 8 min). These measurements should allow forecasters to detect the rapid changes that can lead to tornadic storms in the Southeastern U.S. Further, the assimilation of these data into forecast models should lead to improvements in model skill at forecasting severe storms.

Improve the capability of UAS in mesoscale and boundary layer research. VORTEX-SE has the need for UAS to perform boundary layer profiling, acquire detailed photographic data along tornado damage paths, and to sample the local gradients of wind and thermodynamic variables in boundary layer features on scales of 100 m. If these systems can be used effectively in VORTEX-SE, they will likely become routinely available for future research endeavors.

References

Ashley, W. S., 2007: Spatial and temporal analysis of tornado fatalities in the united states: 1880–2005. *Weather and Forecasting*, **22 (6)**, 1214–1228, doi:10.1175/2007WAF2007004.1, URL `http://dx.doi.org/10.1175/2007WAF2007004.1`.

Ashley, W. S., A. J. Krmenec, and R. Schwantes, 2008: Vulnerability due to nocturnal tornadoes. *Weather and Forecasting*, **23 (5)**, 795–807, doi:10.1175/2008WAF2222132.1, URL `http://dx.doi.org/10.1175/2008WAF2222132.1`.

Atkins, N. T. and M. St. Laurent, 2009: Bow echo mesovortices. part ii: Their genesis. *Monthly Weather Review*, **137 (5)**, 1514–1532, doi:10.1175/2008MWR2650.1, URL `http://dx.doi.org/10.1175/2008MWR2650.1`.

Baker, A. K., M. D. Parker, and M. D. Eastin, 2009: Environmental ingredients for supercells and tornadoes within hurricane ivan. *Weather and Forecasting*, **24 (1)**, 223–244, doi:10.1175/2008WAF2222146.1, URL `http://dx.doi.org/10.1175/2008WAF2222146.1`.

Beck, J. and C. Weiss, 2012: An assessment of low-level baroclinity and vorticity within a simulated supercell. *Monthly Weather Review*, **141 (2)**, 649–669, doi:10.1175/MWR-D-11-00115.1, URL `http://dx.doi.org/10.1175/MWR-D-11-00115.1`.

Bedka, K. M., C. Wang, R. Rogers, L. D. Carey, W. Feltz, and J. Kanak, 2015: Examining deep convective cloud evolution using total lightning, wsr-88d, and goes-14 super rapid scan datasets. *Weather and Forecasting*, doi:10.1175/WAF-D-14-00062.1, URL `http://dx.doi.org/10.1175/WAF-D-14-00062.1`.

Bodine, D. J., M. R. Kumjian, R. D. Palmer, P. L. Heinselman, and A. V. Ryzhkov, 2012: Tornado damage estimation using polarimetric radar. *Weather and Forecasting*, **28 (1)**, 139–158, doi:10.1175/WAF-D-11-00158.1, URL `http://dx.doi.org/10.1175/WAF-D-11-00158.1`.

Brennan, M. J., G. M. Lackmann, and S. E. Koch, 2003: An analysis of the impact of a split-front rainband on appalachian cold-air damming. *Weather and Forecasting*, **18 (5)**, 712–731, doi:10.1175/1520-0434(2003)018⟨0712:AAOTIO⟩2.0.CO;2, URL `http://dx.doi.org/10.1175/1520-0434(2003)018<0712:AAOTIO>2.0.CO;2`.

Brotzge, J. and W. Donner, 2013: The tornado warning process: A review of current research, challenges, and opportunities. *Bulletin of the American Meteorological Society*, **94 (11)**, 1715–1733, doi:10.1175/BAMS-D-12-00147.1, URL `http://dx.doi.org/10.1175/BAMS-D-12-00147.1`.

Brotzge, J. and S. Erickson, 2010: Tornadoes without nws warning. *Weather and Forecasting*, **25 (1)**, 159–172, doi:10.1175/2009WAF2222270.1, URL `http://dx.doi.org/10.1175/2009WAF2222270.1`.

Brotzge, J., S. Erickson, and H. Brooks, 2011: A 5-yr climatology of tornado false alarms. *Weather and Forecasting*, **26 (4)**, 534–544, doi:10.1175/WAF-D-10-05004.1, URL `http://dx.doi.org/10.1175/WAF-D-10-05004.1`.

Brotzge, J. A., S. E. Nelson, R. L. Thompson, and B. T. Smith, 2013: Tornado probability of detection and lead time as a function of convective mode and environmental parameters. *Weather and Forecasting*, **28 (5)**, 1261–1276, doi:10.1175/WAF-D-12-00119.1, URL `http://dx.doi.org/10.1175/WAF-D-12-00119.1`.

Crowe, C. C., C. J. Schultz, M. R. Kumjian, L. D. Carey, and W. A. Petersen, 2012: Use of dual-polarization signatures in diagnosing tornado potential. *Electronic J. Operational Meteor.*, **13 (5)**, 57–58.

Davis, J. M. and M. D. Parker, 2014: Radar climatology of tornadic and nontornadic vortices in high-shear, low-cape environments in the mid-atlantic and southeastern united states. *Weather and Forecasting*, **29 (4)**, 828–853, doi:10.1175/WAF-D-13-00127.1, URL `http://dx.doi.org/10.1175/WAF-D-13-00127.1`.

Forbes, G. S., 1998: Topographic influences on tornadoes in pennsylvania. *Preprints, 19th Conf. on Severe Local Storms*, Minneapolis, MN, American Meteorological Society, 269–272.

Gaudet, B. J. and W. R. Cotton, 2006: Low-level mesocyclonic concentration by nonaxisymmetric transport. part i: Supercell and mesocyclone evolution. *Journal of the Atmospheric Sciences*, **63 (4)**, 1113–1133, doi:10.1175/JAS3685.1, URL `http://dx.doi.org/10.1175/JAS3685.1`.

Knupp, K. R., et al., 2013: Meteorological overview of the devastating 27 april 2011 tornado outbreak. *Bulletin of the American Meteorological Society*, **95 (7)**, 1041–1062, doi:10.1175/BAMS-D-11-00229.1, URL `http://dx.doi.org/10.1175/BAMS-D-11-00229.1`.

Koch, S. E., 2001: Real-time detection of split fronts using mesoscale models and wsr-88d radar products. *Weather and Forecasting*, **16 (1)**, 35–55, doi:10.1175/1520-0434(2001)016⟨0035:RTDOSF⟩2.0.CO;2, URL `http://dx.doi.org/10.1175/1520-0434(2001)016<0035:RTDOSF>2.0.CO;2`.

Koch, S. E. and J. D. Mitchem, 2003: The map room: A structured process for prediction of convection associated with split cold fronts. *Bulletin of the American Meteorological Society*, **84 (2)**, 174–179, doi:10.1175/BAMS-84-2-174, URL http://dx.doi.org/10.1175/BAMS-84-2-174.

Lee, B. D. and R. B. Wilhelmson, 1997: The numerical simulation of non-supercell tornadogenesis. part i: Initiation and evolution of pretornadic misocyclone circulations along a dry outflow boundary. *Journal of the Atmospheric Sciences*, **54 (1)**, 32–60, doi:10.1175/1520-0469(1997)054⟨0032:TNSONS⟩2.0.CO;2, URL http://dx.doi.org/10.1175/1520-0469(1997)054<0032:TNSONS>2.0.CO;2.

Lewellen, D. C., 2012: Effects of topography on tornado dynamics: A simulation study. *Preprints, 26th Conf. on Severe Local Storms*, American Meteorological Society, Nashville, TN, 4B.1.

Markowski, P. M. and N. Dotzek, 2011: A numerical study of the effects of orography on supercells. *Atmospheric Research*, **100 (4)**, 457–478, doi:10.1016/j.atmosres.2010.12.027, URL http://dx.doi.org/10.1016/j.atmosres.2010.12.027.

Markowski, P. M., J. M. Straka, and E. N. Rasmussen, 2002: Direct surface thermodynamic observations within the rear-flank downdrafts of nontornadic and tornadic supercells. *Monthly Weather Review*, **130 (7)**, 1692–1721, doi:10.1175/1520-0493(2002)130⟨1692:DSTOWT⟩2.0.CO;2, URL http://dx.doi.org/10.1175/1520-0493(2002)130<1692:DSTOWT>2.0.CO;2.

Sherburn, K. D. and M. D. Parker, 2014: Climatology and ingredients of significant severe convection in high-shear, low-cape environments. *Weather and Forecasting*, **29 (4)**, 854–877, doi:10.1175/WAF-D-13-00041.1, URL http://dx.doi.org/10.1175/WAF-D-13-00041.1.

Sutter, D. and K. M. Simmons, 2009: Tornado fatalities and mobile homes in the united states. *Nat Hazards*, **53 (1)**, 125–137, doi:10.1007/s11069-009-9416-x, URL http://dx.doi.org/10.1007/s11069-009-9416-x.

Szoke, E. J., M. L. Weisman, J. M. Brown, F. Caracena, and T. W. Schlatter, 1984: A subsynoptic analysis of the denver tornadoes of 3 june 1981. *Monthly Weather Review*, **112 (4)**, 790–808, doi:10.1175/1520-0493(1984)112⟨0790:ASAOTD⟩2.0.CO;2, URL http://dx.doi.org/10.1175/1520-0493(1984)112<0790:ASAOTD>2.0.CO;2.

Thompson, R. L., B. T. Smith, A. R. Dean, and P. T. Marsh, 2013: Spatial distributions of tornadic near-storm environments by convective mode. *Electronic J. Severe Storms Meteor.*, **8 (5)**, 1–22.

Trapp, R. J. and M. L. Weisman, 2003: Low-level mesovortices within squall lines and bow echoes. part ii: Their genesis and implications. *Monthly Weather Review*, **131 (11)**, 2804–2823, doi:10.1175/1520-0493(2003)131⟨2804:LMWSLA⟩2.0.CO;2, URL `http://dx.doi.org/10.1175/1520-0493(2003)131<2804:LMWSLA>2.0.CO;2`.

Van Den Broeke, M. S. and S. T. Jauernic, 2014: Spatial and temporal characteristics of polarimetric tornadic debris signatures. *Journal of Applied Meteorology and Climatology*, **53 (10)**, 2217–2231, doi:10.1175/JAMC-D-14-0094.1, URL `http://dx.doi.org/10.1175/JAMC-D-14-0094.1`.

Weisman, M. L. and R. J. Trapp, 2003: Low-level mesovortices within squall lines and bow echoes. part i: Overview and dependence on environmental shear. *Monthly Weather Review*, **131 (11)**, 2779–2803, doi:10.1175/1520-0493(2003)131⟨2779:LMWSLA⟩2.0.CO;2, URL `http://dx.doi.org/10.1175/1520-0493(2003)131<2779:LMWSLA>2.0.CO;2`.

Wheatley, D. M. and R. J. Trapp, 2008: The effect of mesoscale heterogeneity on the genesis and structure of mesovortices within quasi-linear convective systems. *Monthly Weather Review*, **136 (11)**, 4220–4241, doi:10.1175/2008MWR2294.1, URL `http://dx.doi.org/10.1175/2008MWR2294.1`.

Wicker, L. J. and R. B. Wilhelmson, 1995: Simulation and analysis of tornado development and decay within a three-dimensional supercell thunderstorm. *Journal of the Atmospheric Sciences*, **52 (15)**, 2675–2703, doi:10.1175/1520-0469(1995)052⟨2675:SAAOTD⟩2.0.CO;2, URL `http://dx.doi.org/10.1175/1520-0469(1995)052<2675:SAAOTD>2.0.CO;2`.